Black Holes in Binary Systems and Galaxy Nuclei

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Overview:

1. Introduction: 40 years of BHs investigations.
2. Observations of stellar mass BHs in X-ray binary systems.
3. Stellar mass BH demography.
4. Observations of supermassive BHs in galactic nuclei.
5. Supermassive BH demography.
6. Conclusion.
7. Future investigations.

I. Introduction.

Importance of the searchers for BHs was stressed by V.L.Ginzburg in his list of the most important problems in modern physics and astrophysics (Ginzburg, 1995).

According to modern theory of stellar evolution taking into account Einstein General Relativity, if:

$$M_{star}^{core} > 3M_{Sun} \Rightarrow BH,$$

$$M_{star}^{core} < 3M_{Sun} \Rightarrow NS \text{ or } WD.$$

BH event horizon r_h:

$$r_h = r_g = \frac{2GM}{c^2}$$

for non-rotating (Schwarzschild) BH,

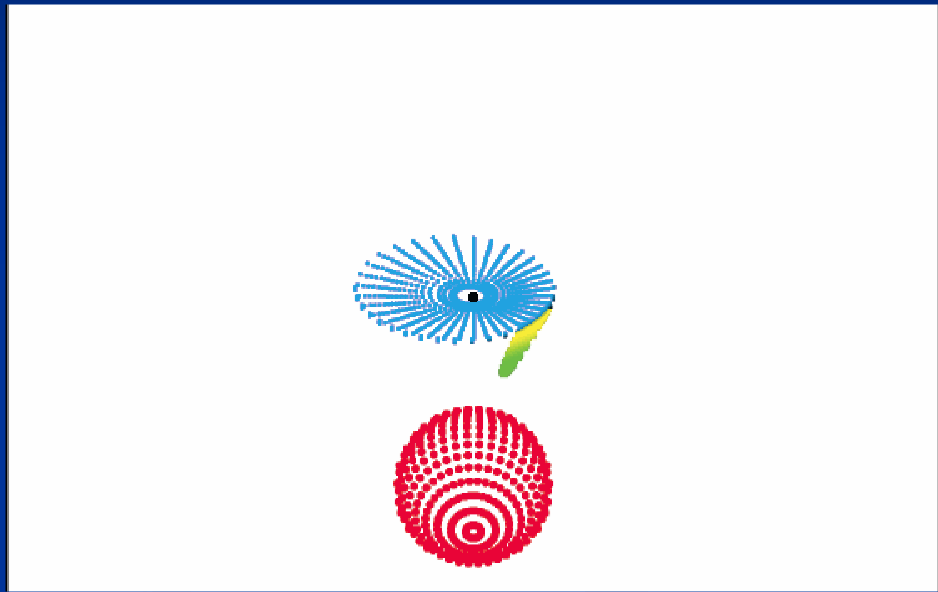
$$r_h < r_g$$

for rotating BH.

r_g = 9 mm for the Earth, r_g = 3 km for the Sun,

r_g = 40 AU for $M_{BH} = 2 \cdot 10^9 \ M_{Sun}$

- 40 years ago first Black Hole candidate (Cyg X-1) has been discovered in X-ray binary system.
- X-ray binary: optical star – donor of matter and accreting relativistic object – neutron star (NS) or black hole (BH).



R. Giacconi – Nobel Prize (2002)

II. Observations of stellar mass BHs in X-ray binaries.

Theoretical prediction of X-ray from accreting BH:

- Zeldovich (1964) and Salpeter (1964) – strong energy release from non-spherical accretion onto BH.
- Pringle and Rees (1972)
- Shakura and Sunyaev (1973)
- Novikov and Thorne (1973)

} – theory of disk accretion onto BH.

First X-ray observations of accreting BHs in X-ray binary systems:

Giacconi et al. (1972) – UHURU epoch.

~100 compact X-ray sources, most of which are X-ray binaries.

First X-ray binaries: Cyg X-1, Her X-1, Cen X-3, Vela X-1, SMC X-1, etc.

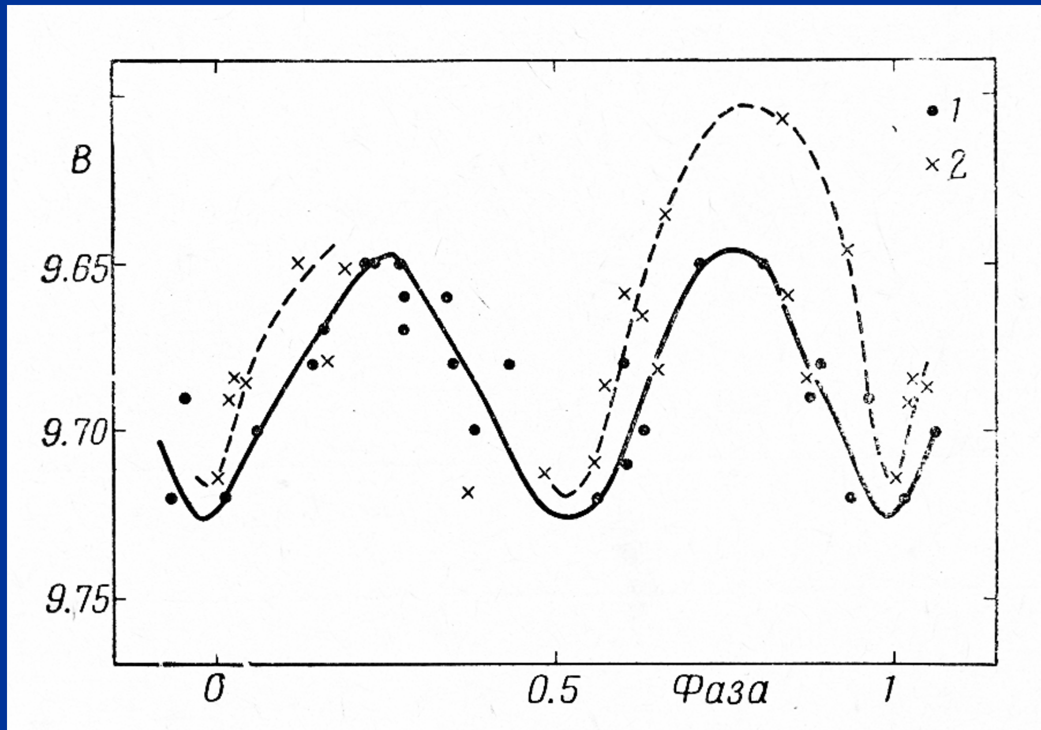
First optical identifications of X-ray binaries: ellipticity and reflection effects.

Cherepashchuk, Efremov, Kurochkin, Shakura, Sunyaev, 1972,

J. Bahcall, N. Bahcall, 1972,

Lyutyi, Sunyanev, Cherepashchuk, 1973

Cyg X-1



- Up to now from the borders of many special X-ray space observatories (Einstein, Rosat, XMM Newton, Integral etc.) several thousands of X-ray binaries have been discovered.
- Optical investigations made by many scientific groups (USA, England, Germany, Russia etc.) allowed to estimate the masses of 26 stellar mass BHs in X-ray binary systems.
- Up to now masses of ~50 NS in binary systems have been determined.

Determination of BH masses in X-ray binaries

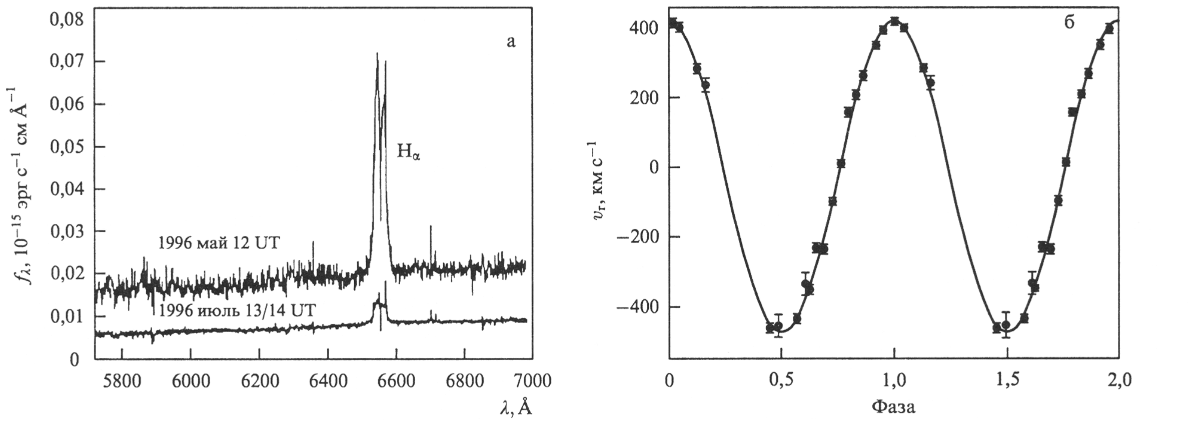
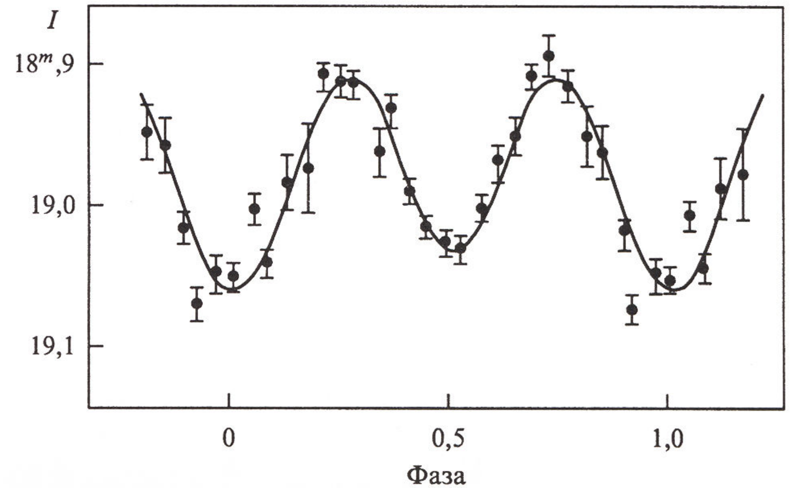
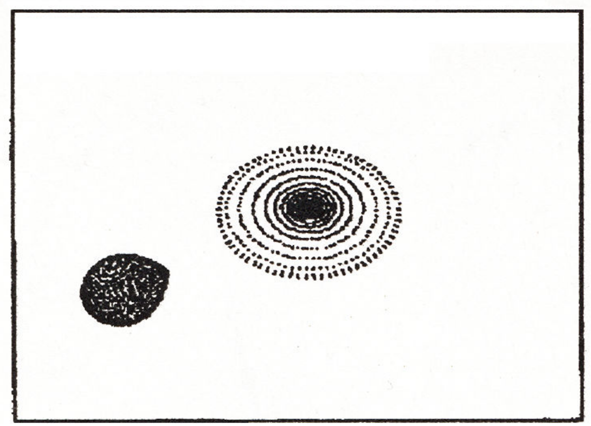
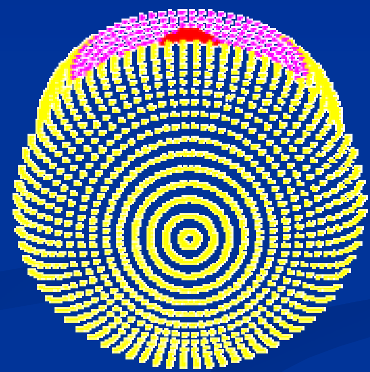


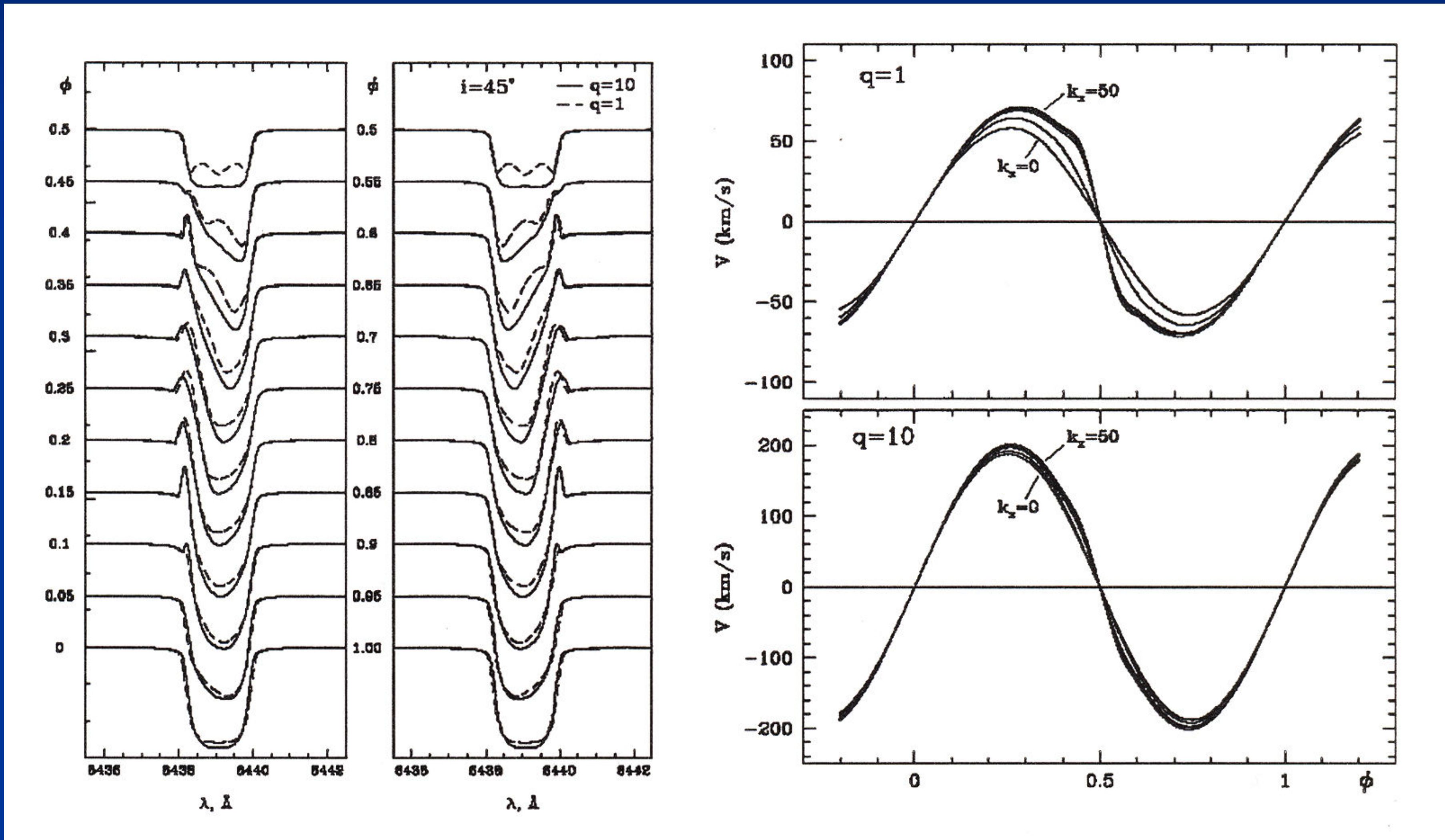
Рис. 3. (а) Оптические спектры рентгеновской новой — двойной системы с ЧД Nova Oph 1977 (H 1705 – 250) в спокойном состояни полученные Филиппенко и др. [91] 12 мая и 13 – 14 июля 1996 г. Видны многочисленные линии поглощения в спектре спутника — звезд K5 V, по доплеровским смещениям которых строится кривая лучевых скоростей. Также видна мощная широкая и двугорбая эмиссионна линия водорода H_α, сформированная в аккреционном диске, вращающемся вокруг ЧД. (б) Кривая лучевых скоростей [91].





- Recently new methods of interpretation of the light curves, line profiles and radial velocity curves have been developed in our group. In these methods tidal and rotational deformations of the optical star are taken into account. X-ray heating effect as well as the eclipsing effects are taken into account too (Antokhina, Cherepashchuk, Shimansky, 2003, 2005).

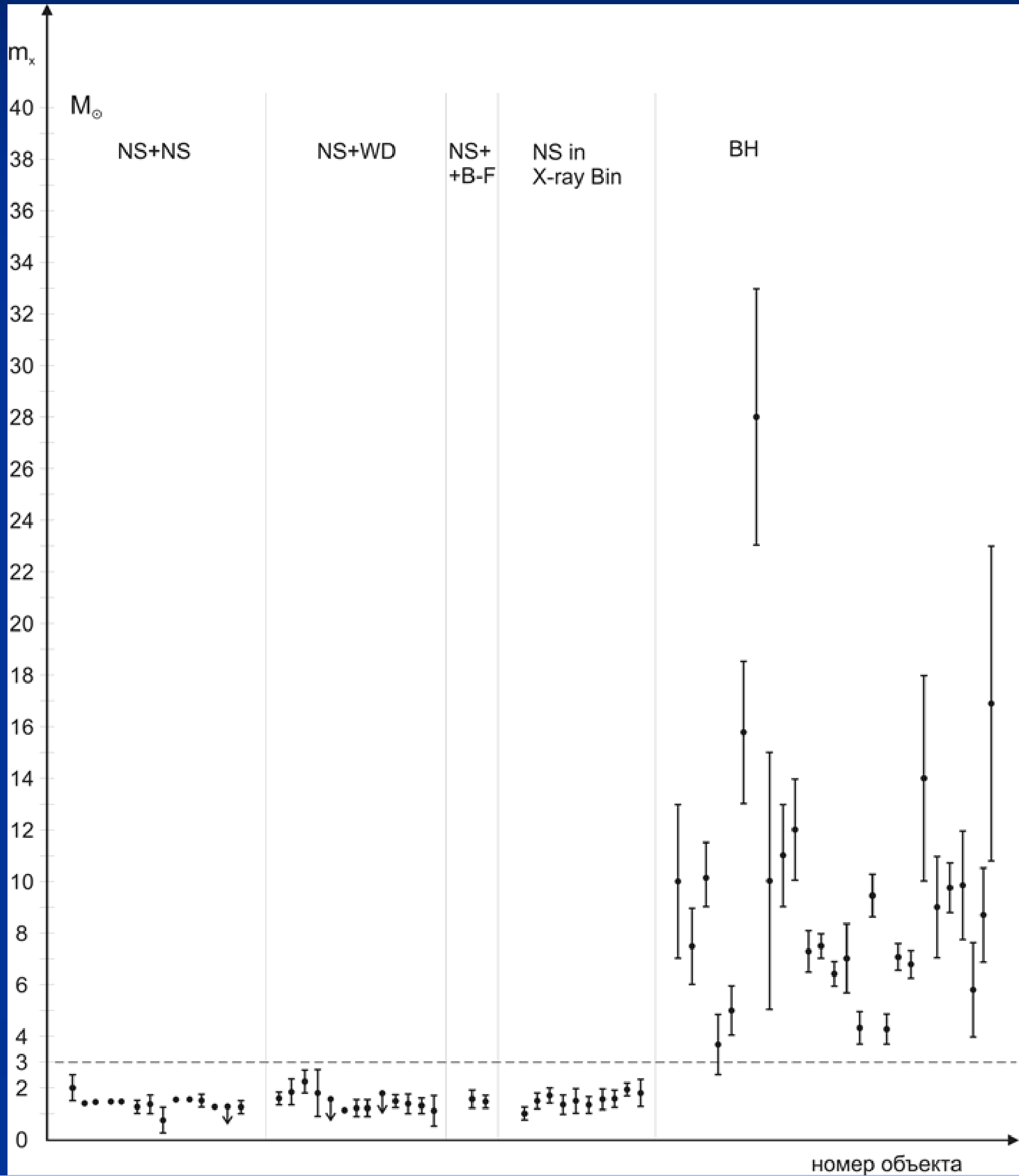




φ
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
6436
6438
6440
6442
λ, Å
φ
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1.00
i=45°
q=10
q=1
6436
6438
6440
6442
λ, Å
q=1
k_z=50
k_z=0
V (km/s)
100
50
0
−50
−100
q=10
k_z=50
k_z=0
V (km/s)
200
100
0
−100
−200
0
0.5
1
φ

Masses, dimensions and spins of BHs in X-ray binary systems.

- Up to now masses of 26 stellar mass BH and ~50 NS have been estimated in binary systems. $M_{BH} = 4 - 25\ M_{Sun}$.
- Masses of 50 NS lie in the range $(1 - 2)\ M_{Sun}$. Mean mass of the NS is $\sim 1.4\ M_{Sun}$.



- Radii of BH candidates are estimated using rapid X-ray variability:

$$\Delta t \approx 10^{-3}\ \mathrm{s},$$

$$r \leq c\Delta t \approx 300\ \mathrm{km} = 10\ r_g.$$

- BH spins are measured basically by X-ray continuum-fitting method (McClintock et al., 2011), using relativistic thin-disk model of Novikov and Thorne (1973).

- NS with measured masses are X-ray pulsars, radiopulsars or X-ray bursters of the first kind. All these properties are the evidences of the observed surface of NS.
- Therefore, in all 50 cases when the relativistic object shows evidences of the observed surface its mass does not exceed the value 3 M_{Sun} – absolute upper limit of the mass of NS predicted by the Einstein General Relativity (!).

- Masses of 26 BH lie in the range (4 - 25) M_{Sun}. Mean mass of the BH is ~9 M_{Sun}. None of this 26 BH candidates is X-ray pulsar, radiopulsar or X-ray burster of the first kind. Therefore none of these massive ($m_x > 3\ M_{Sun}$) compact objects shows the evidence of observed surface in agreement with the predictions of the Einstein General Relativity (!).

- So, basic conclusion based on the 40 years of investigations of the relativistic objects in binary systems can be formulated as follows: NS and BH are different from each other not only by the masses, but also by the observational appearances in full agreement with the Einstein General Relativity.

- It should be stressed however, that some NS can not show direct evidences of the observed surfaces. In particular, if rotational axes of the NS coincides with the axes of magnetic dipole, the phenomenon of the X-ray pulsar or radiopulsar can not be observed for NS. Therefore all observational evidences for the BH described above are only necessary but not sufficient.

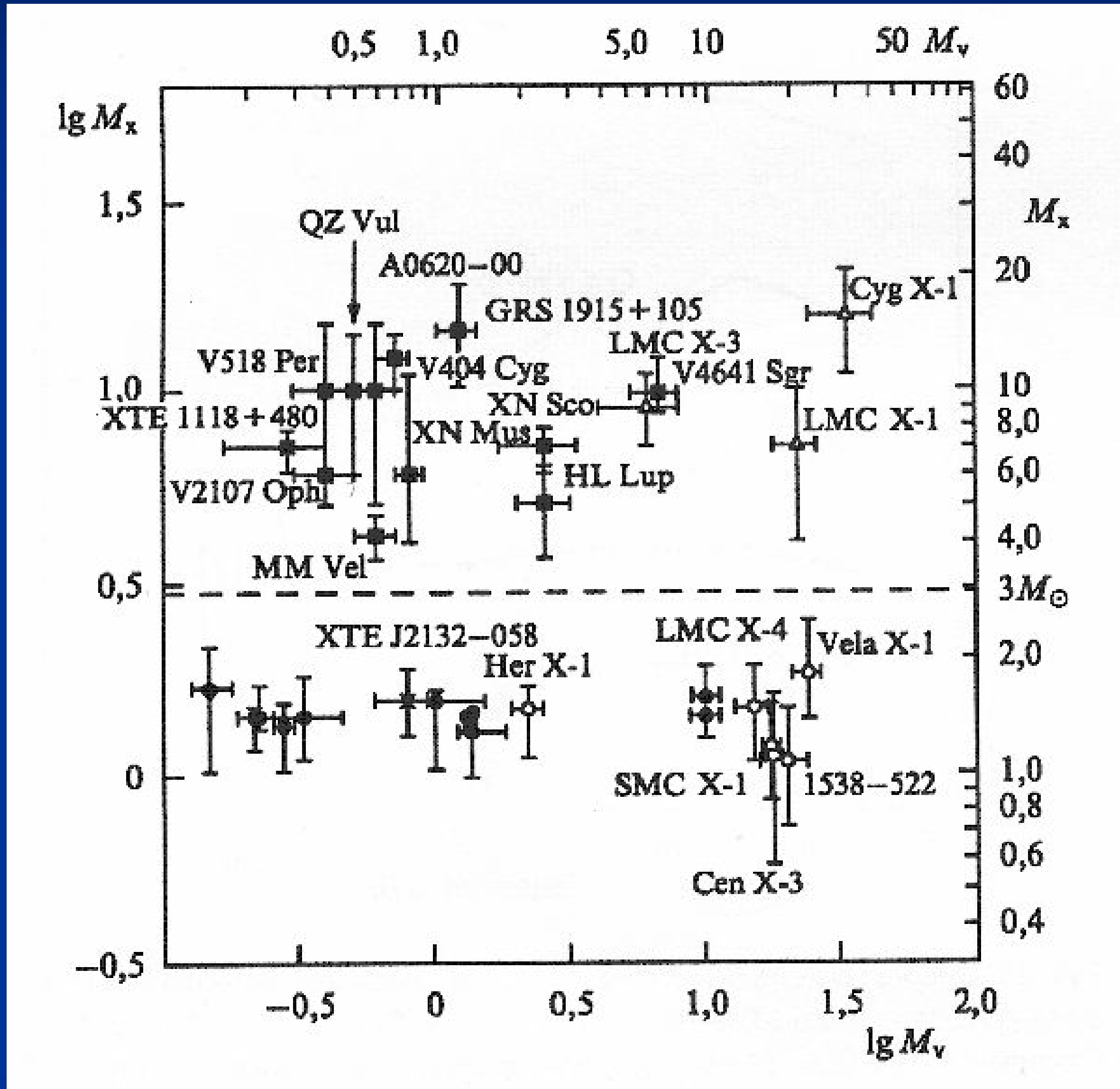
- However, big number of BH candidates (26) allows us to believe in real existence of stellar mass BH in the Universe.
- High value of spin parameter a_* for some BH candidates in X-ray binaries (e.g., GRS 1915+105, $a_* = 0.98$) may be considered as strong evidence for real existence of BHs.

- Recently, due to operation of new generation optical 8 – 10 meter telescopes, the optical investigations of X-ray binary systems in some other galaxies have been realized (e.g., Orosz et al., 2007). Due to these investigations the many new mass determinations for stellar mass BH in X-ray binaries will be obtained.

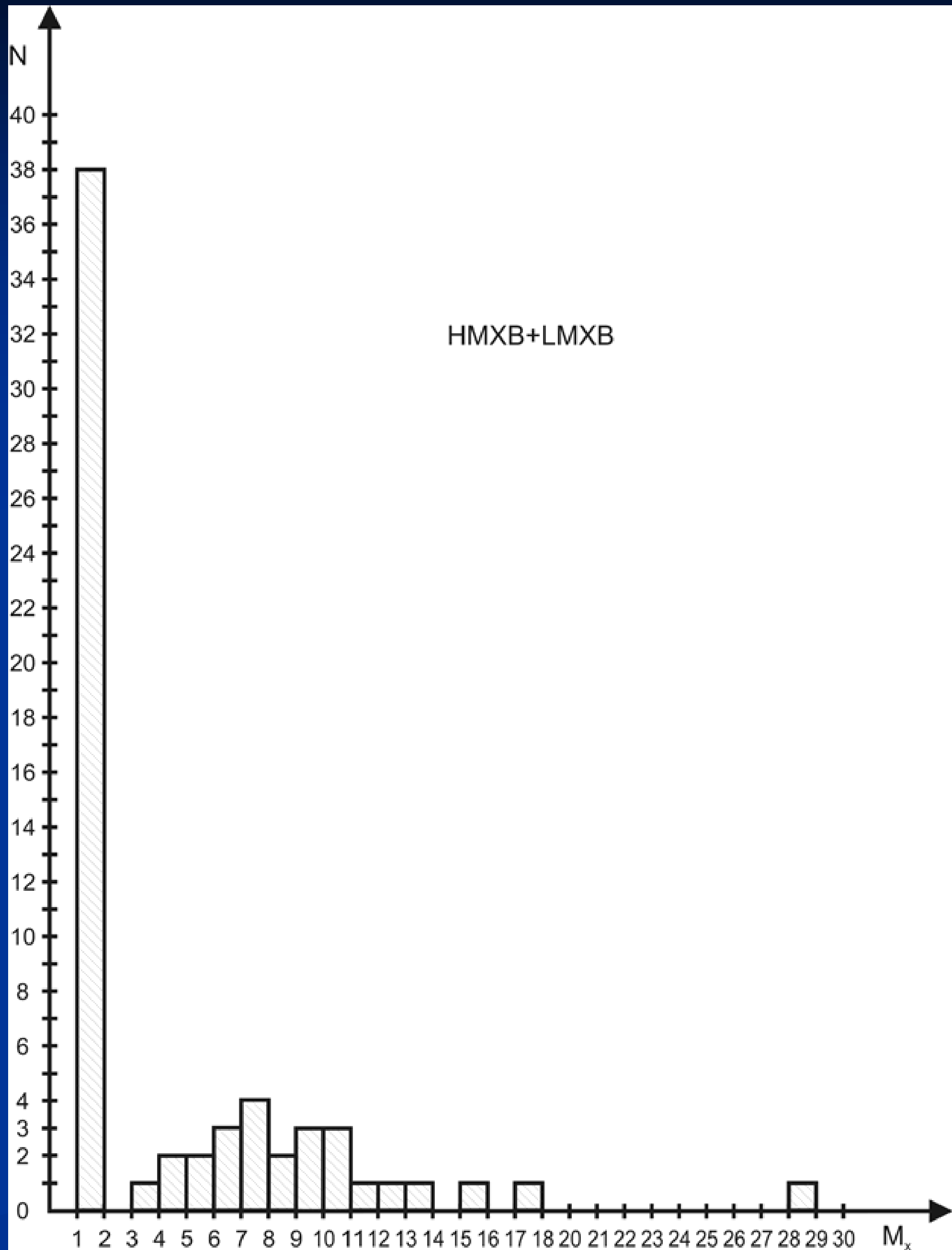
- Up to now the spins of BHs in 9 X-ray binaries have been measured. 5 BHs are in X-ray Novae: A 0620-00, XTE J1550-564, GRO J1655-40, GRS 1915+105, 4U 1543-47 (Remillard and McClintock, 2006), and 4 BHs are in persistent X-ray binaries: LMC X-3 (Davis et al., 2006), M33 X-7 (Lin et al., 2008, 2010), LMC X-1 (Gou et al., 2009), Cyg X-1 (Gou et al., 2011). Dimensionless spin parameter $a_* = cJ/GM^2$. $a_* \approx$ 0.98 (GRS 1915+105) ÷ 0.12 (A 0620-00).

III. Stellar mass BH demography.

- There is no correlation between masses of relativistic objects and those of companion stars in binary systems.



- Number of BHs does not increase with decreasing of their masses.
- It seems to be strange because the number of stars in The Galaxy – progenitors of BHs ($M > 30\ M_{Sun}$) is strongly increasing with decreasing of their masses: $N \sim M^{-5}$.



- It can be shown (e.g., Cherepashchuk, 2003) that this peculiarity in the mass distribution for BH is not due to observational selection effects (disruption of binary system after supernova explosion, strong mass loss by the star due to stellar wind etc).

- The gap in the range (2 – 4) M_{Sun} in the mass distribution of NS and BH can be suggested (Bailyn et al., 1998; Cherepashchuk, 1998). In this range (2 – 4) M_{Sun} the number of NS and BH discovered in binary systems up to now is close to zero.
- It can be shown that this gap is not due to observational selection effects (Cherepashchuk, 2001, 2003; Özel at al., 2010; Farr et al., 2011).

- Therefore, there are grounds to suggest that stellar mass BH formation is determined not only by the mass of the progenitor star, but also by other parameters: rotation, magnetic field, instabilities during the collapse of the stellar core etc. (e.g. Fryer and Kalogera, 2001; Postnov and Prokhorov, 2001; Cherepashchuk, 2001; Belczynski et al., 2011).

- Some new possibility to explain peculiarities in the mass distribution of BHs has been considered by Postnov and Cherepashchuk (2003). Deficit of low-mass BH and the gap in the range (2 – 4) M_{Sun} may be due to enhanced quantum evaporation of BH which have been suggested in some multidimensional models of gravity (e.g. Randall and Sundrom, 1999). In these models of gravity the characteristic time of quantum evaporation of BH is much less than that in the Hawking (1974) mechanism.

- Normalized jet power as estimated from the maximum radio flux of ballistic jets is in good correlation with measured spin parameter a_* of the BH (Narayan and McClintock, 2012): $P_{jet} \sim a_*^2$. It is in agreement with the idea that jets may be powered by BH spin energy (Blanford and Znajek, 1977; Tchekhovskoy et al., 2010).

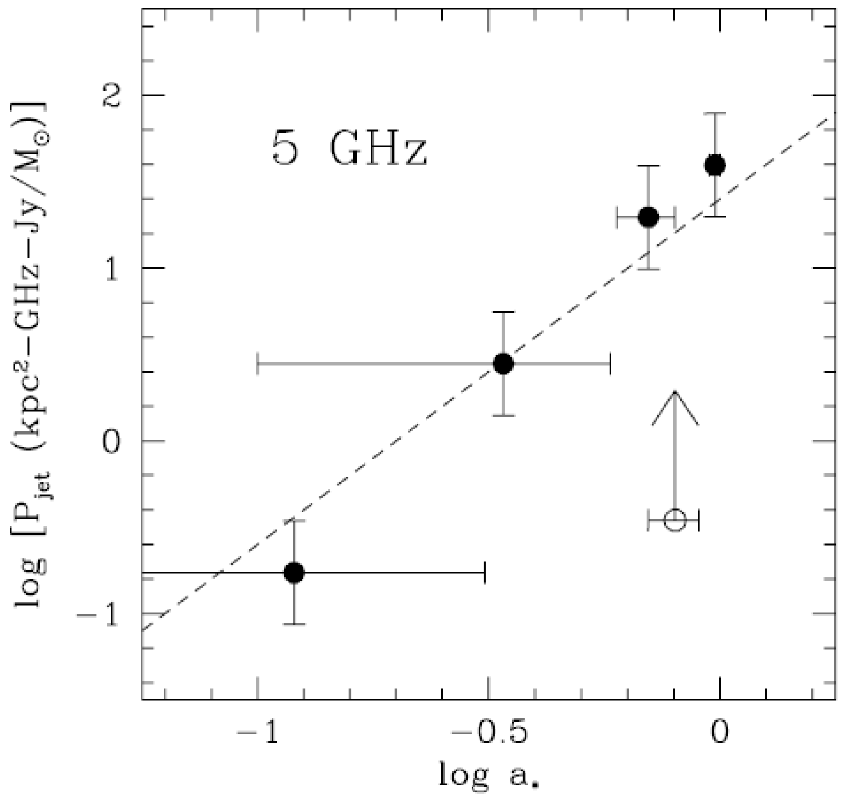


Figure 2. Plot of the jet power P_{jet} as estimated from the maximum radio flux of ballistic jets (equation 1) versus the measured spin parameter of the BH a_* for the transient BHBs in our sample. Solid circles correspond to the first four objects listed in Table 1, which have high-quality radio data, and the open circle corresponds to 4U 1543−47, which has only a lower limit on the jet power. The dashed line corresponds to $P_{jet} \propto a_*^2$, the theoretical scaling derived by Blandford & Znajek (1977). The data suggest that ballistic jets derive their power from the spin of the central BH.

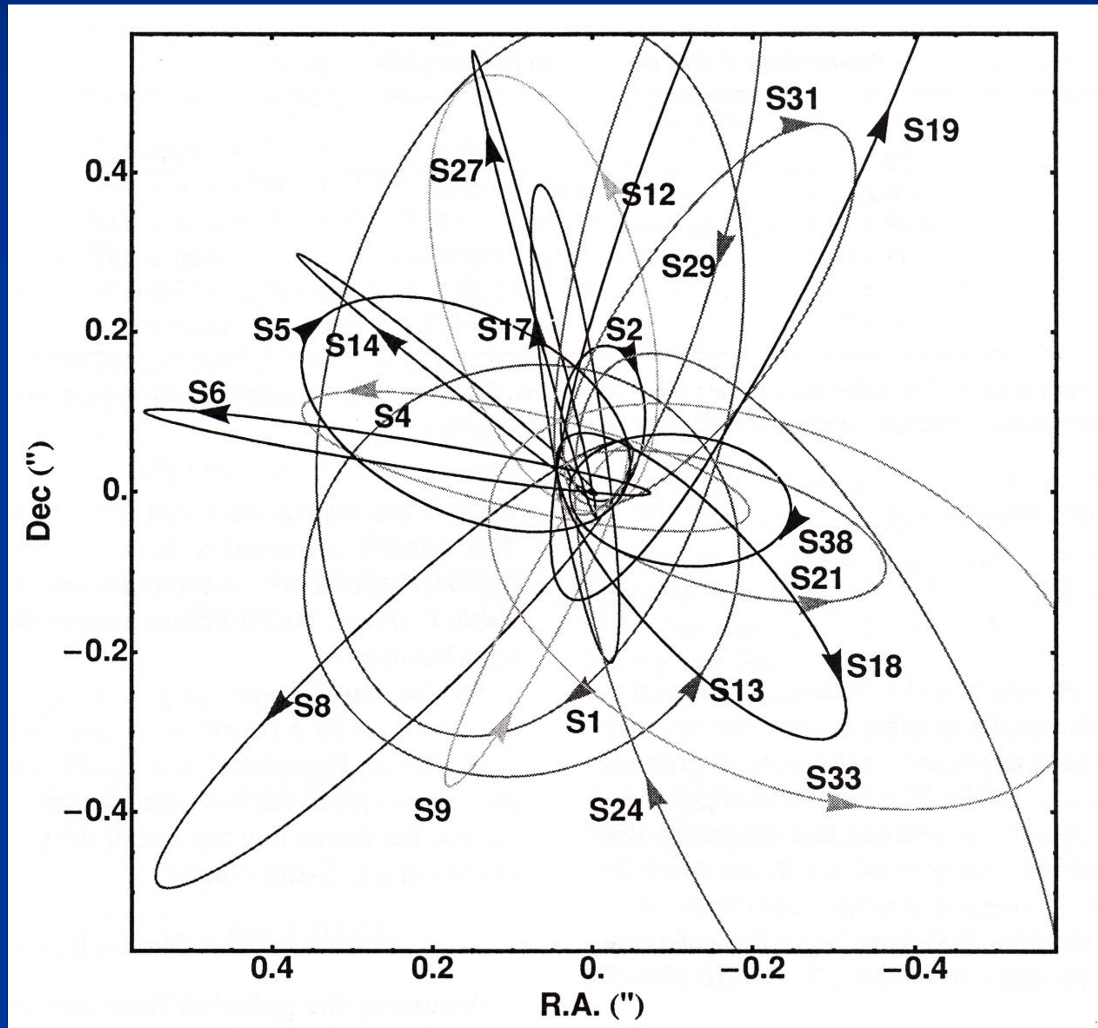
Narayan and McClintock, 2012

IV. Observations of supermassive BHs in galactic nuclei.

Two basic direct methods of the supermassive BH mass determination.

1. Resolved kinematics method.

   Direct observations of the motion of the "probe bodies" in the gravitational field of BH (stars, gaseous disks etc.).

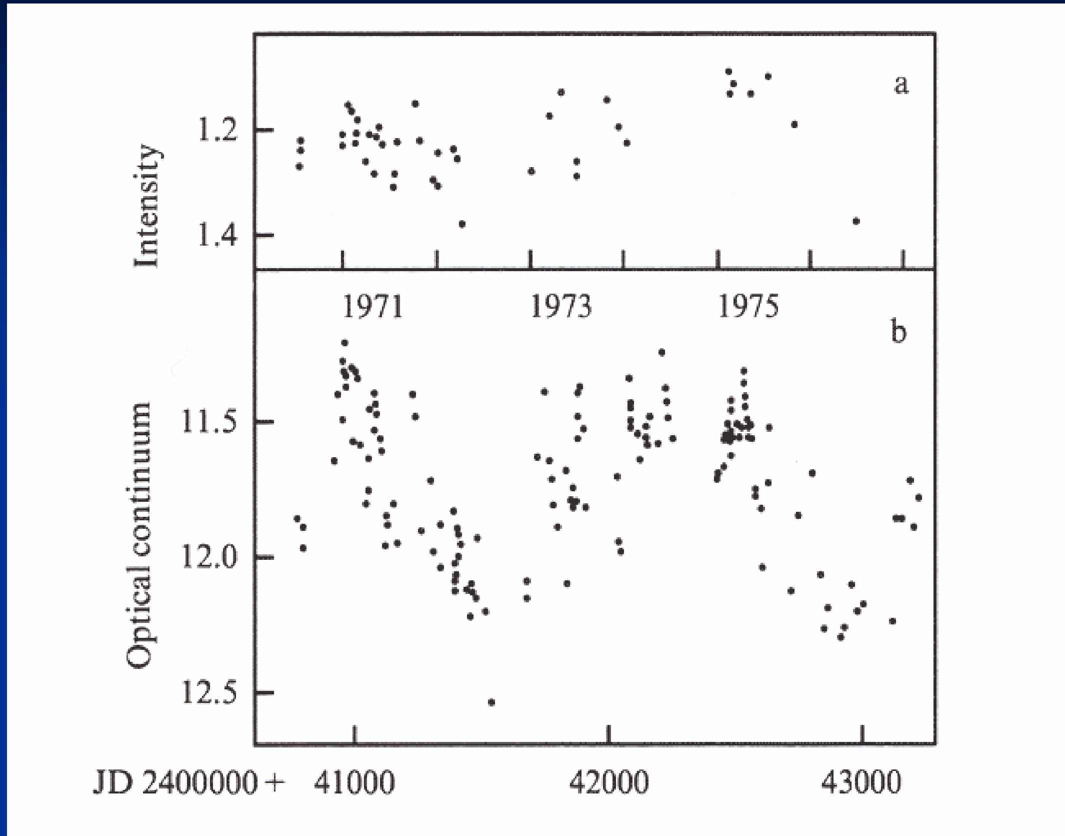


Gillessen et al., 2009

2. Reverberation mapping method.

Observations of time delay Δt between variability of emission lines and continuum in galactic nucleus (Cherepashchuk and Lyutyi, 1973).

r ≈ c · Δt.



$$M_{BH} = \frac{\eta v^2 r}{G}, \quad \eta = 1-3$$

v – from the width of emission line profile

There are several non-direct methods of BH mass determinations in the galactic nuclei. They are calibrated using the results of the most reliable BH mass determinations, obtained by resoled kinematics and reverberation mapping methods.

Up to now more than 100 of reliable determinations of the masses of supermassive BHs in galactic nuclei have been obtained:

$$M_{BH} = 10^6 - 10^{10}\ M_{Sun}$$

V. Supermassive BH demography.

Up to now more than dozen of bright quasars ($M_{BH} \approx 10^8 - 10^9\ M_{Sun}$) with high redshifts

$$z = 6 - 8$$

have been discovered.

Therefore the characteristic growing time for the mass of supermassive BHs is less then 10^9 years.

There is correlation between M_{BH} and M_{buldge}, M_{BH} and σ_{buldge} (velocity dispersion of stars in the buldge):

$$M_{BH} \sim M_{buldge}^{0.95 \pm 0.05} \quad (M_{BH} = 0.001\ M_{buldge})$$

$$M_{BH} \sim \sigma_{\ buldge}^{\alpha} \qquad (\alpha \approx 4 - 5)$$

Some correlation between M_{BH} and asymptotic rotational velocity of galaxy V_{FAR} has been suspected (Ferrarese, 2002; Baes et al., 2003).

Full mass of the galaxy is determined by V_{FAR}: baryonic matter (~10%) and dark matter (~90%).

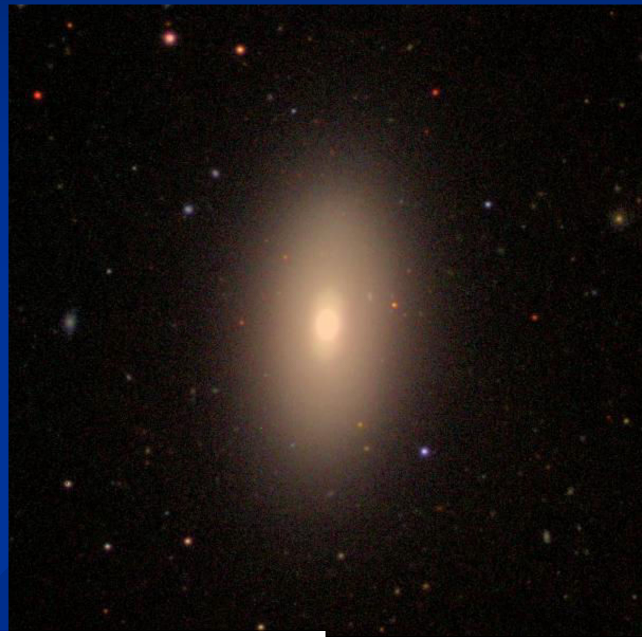
Fundamental dependence $M_{BH}(V_{FAR})$ may be expected from the theoretical grounds (Silk and Rees, 1998; Gurevich et al., 2003).

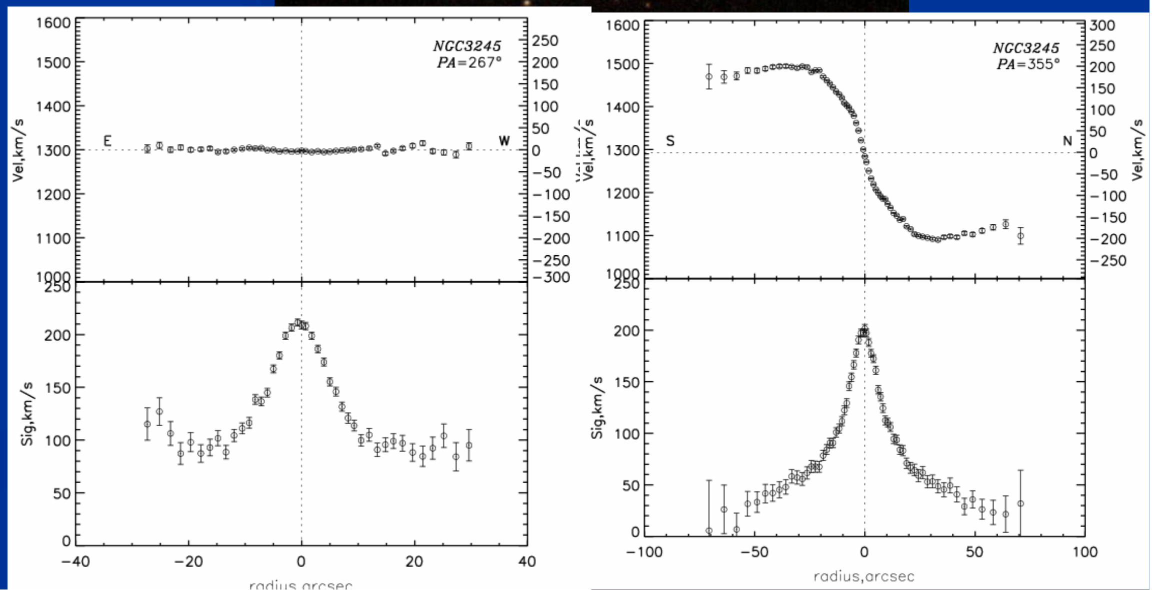
Deep cusps are formed in the protogalactic clouds (consisting basically of dark matter) during their evolution due to gravitational instability.

Observations of rotational velocities of the galaxies with known masses of central supermassive BHs

(Cherepashchuk, Afanasiev, Zasov, Katkov, 2010)

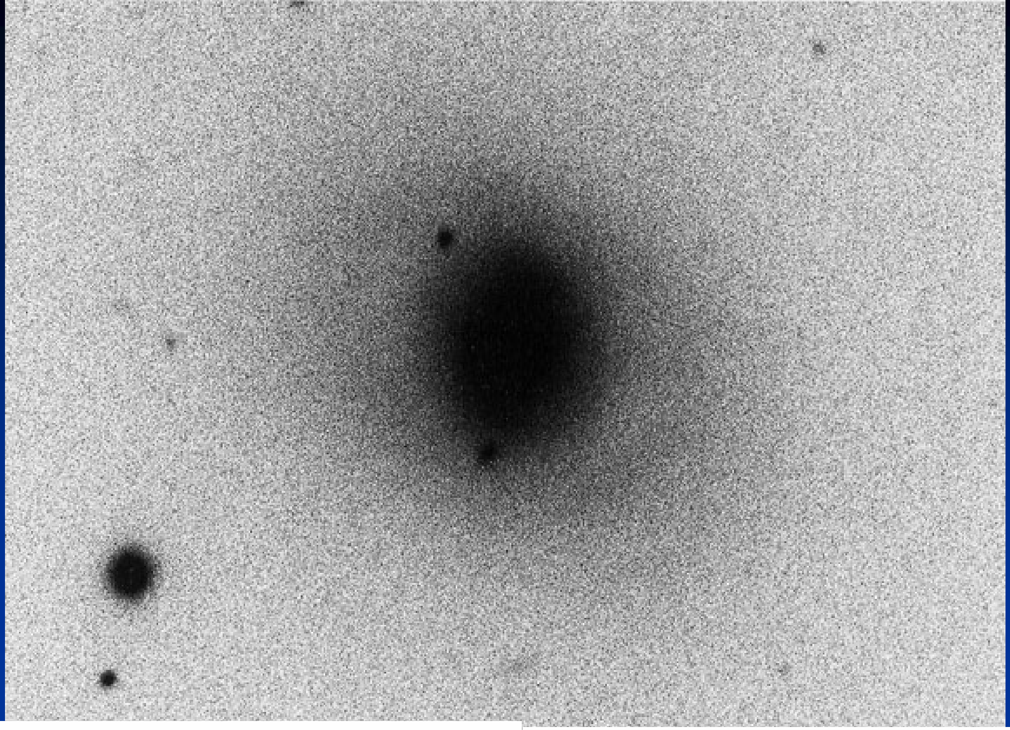
6-meter telescope of SAO RAS

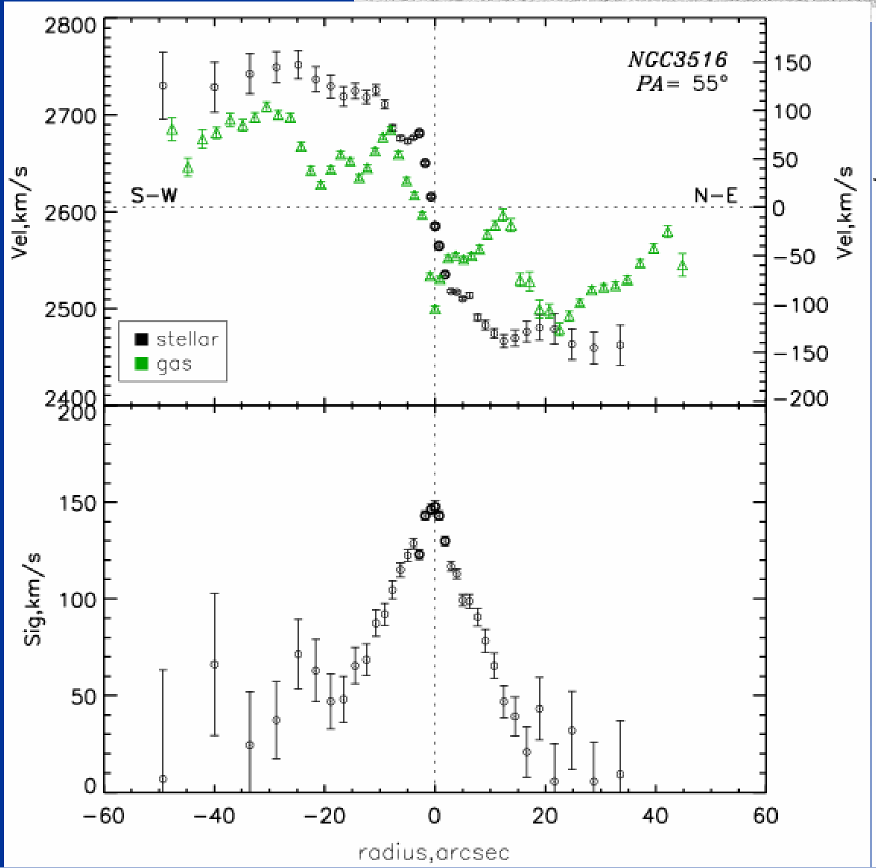


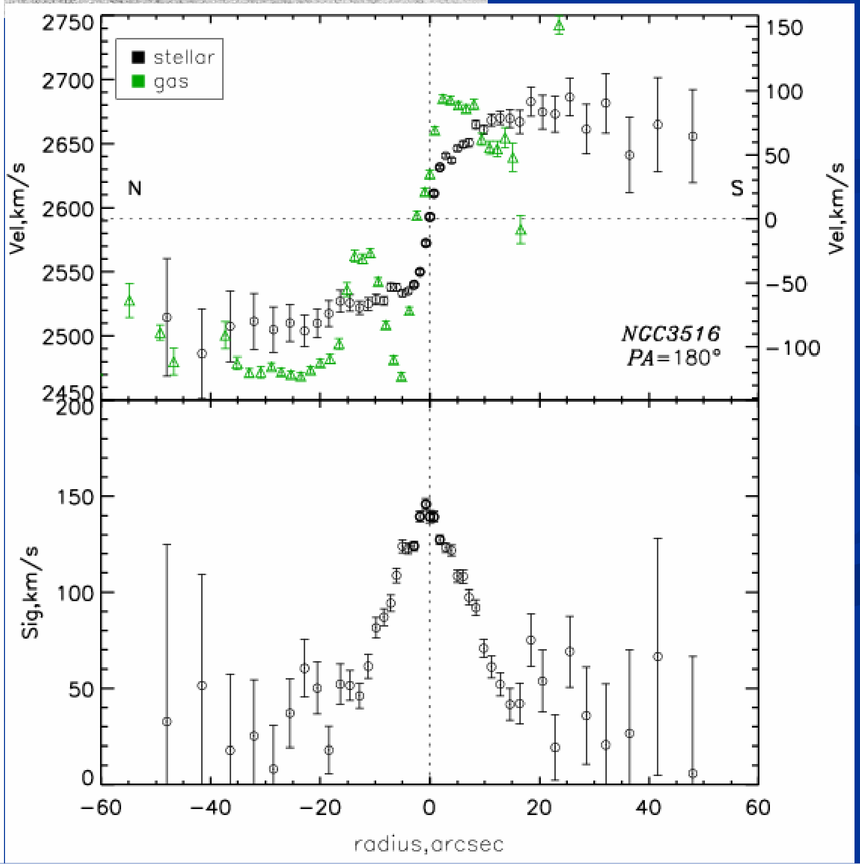


NGC 3245

NGC 3516




NGC3516
PA= 55°
S-W
N-E
stellar
gas
Vel,km/s
Sig,km/s
radius,arcsec


stellar
gas
N
S
NGC3516
PA=180°
Vel,km/s
Sig,km/s
radius,arcsec

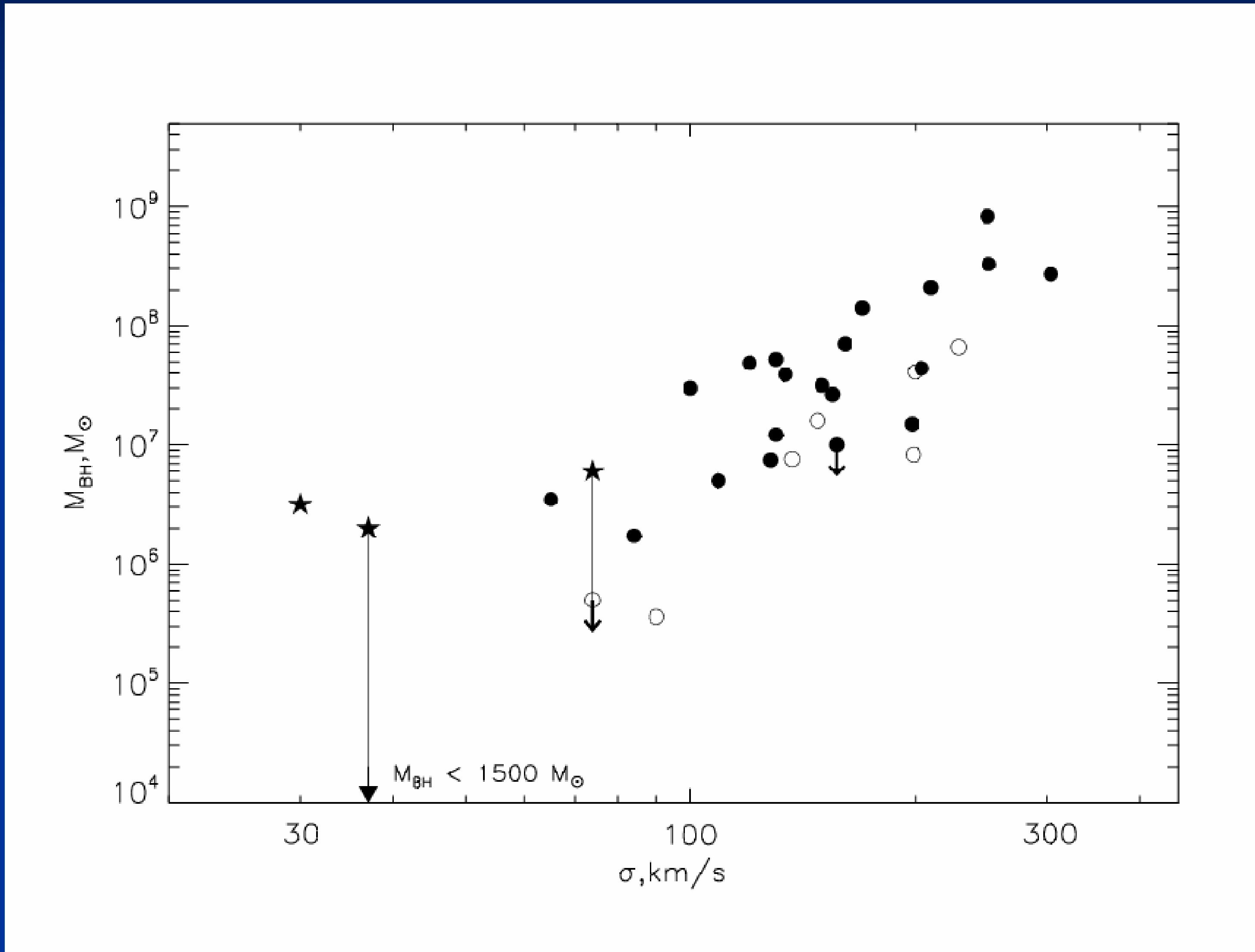
Basic sources on M_{BH}:

- Ferrarese and Ford, 2004
- Peterson, Ferrarese, Gilbert, 2004
- Graham, 2008
- Gultekin, Cackett, Miller, 2009

M_{BH} are determined by resolved kinematics and reverberation mapping methods.

45 galaxies

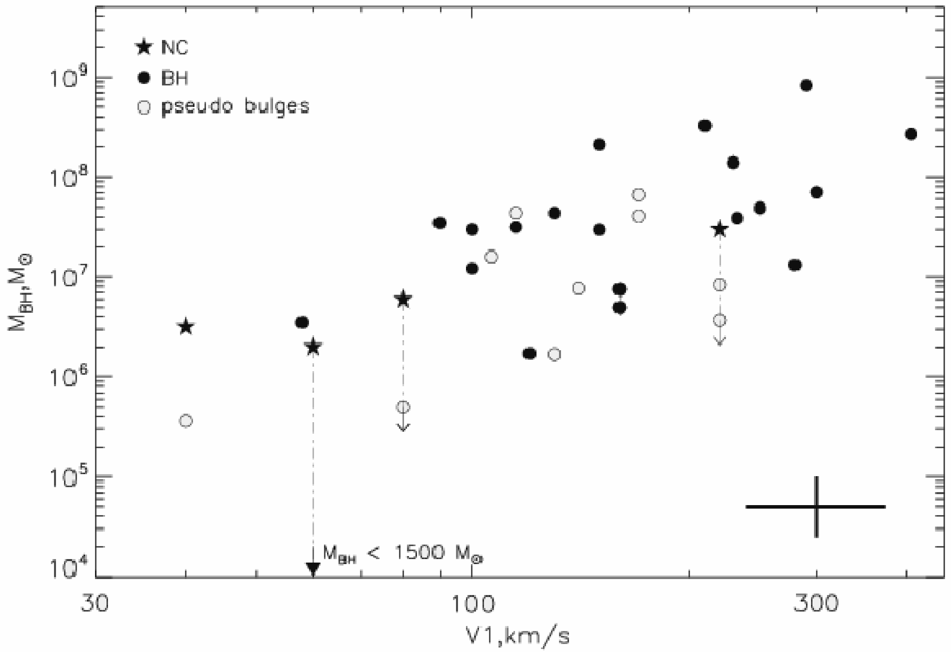
Correlation M_{BH} (σ)

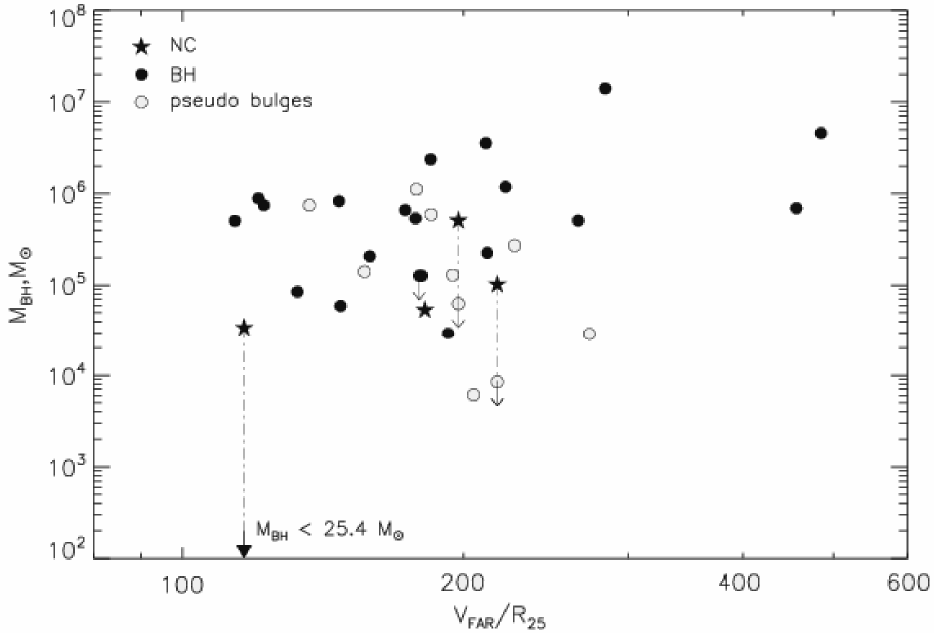


●● - BHs, ★ - nuclear clusters,

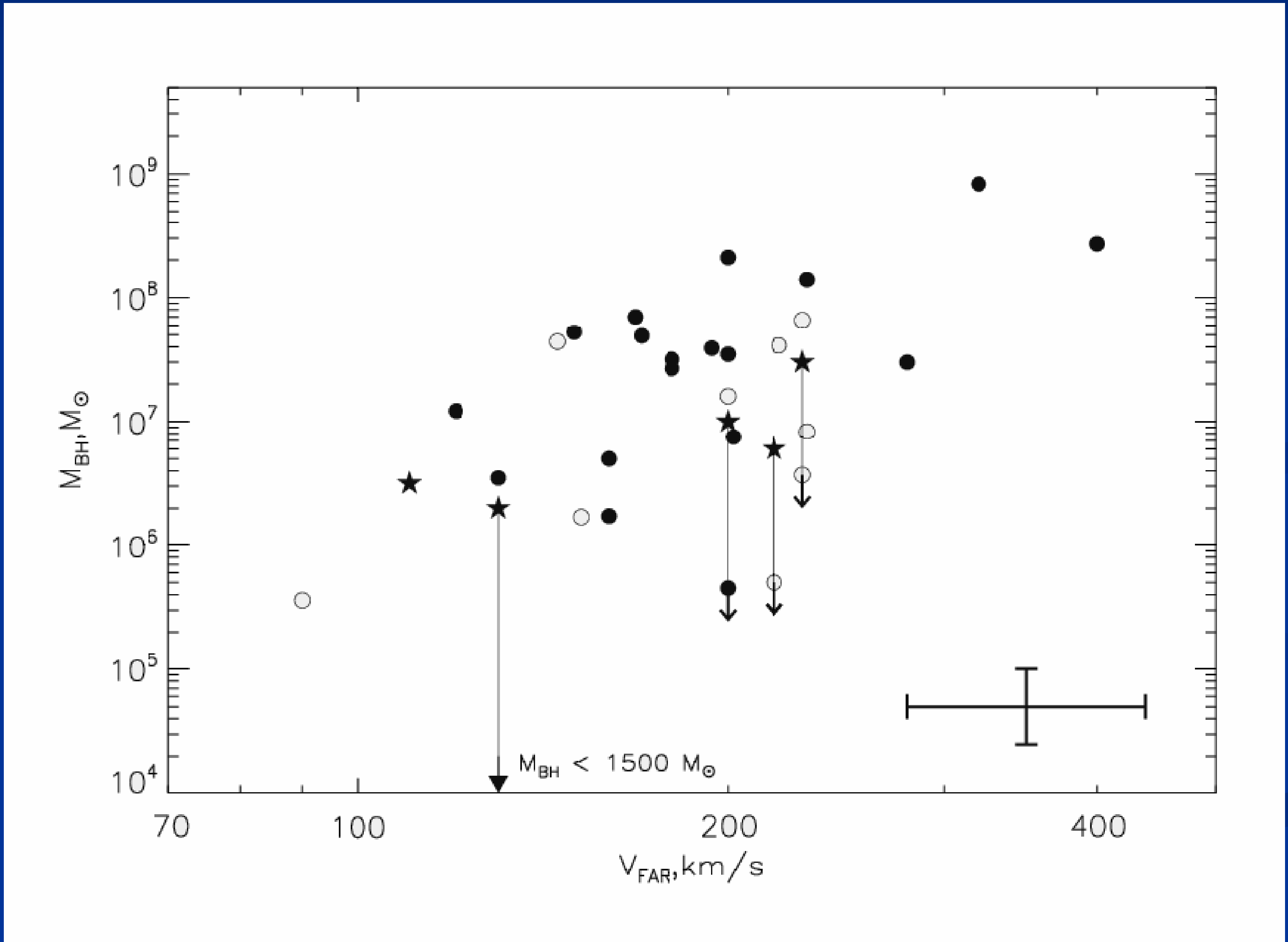
Correlations between M_{BH} and V(R):

R=1 kpc | $R=R_{25}$





Correlation between M_{BH} and asymptotic rotational velocity V_{FAR}



Correlation between M_{BH} and full mass of the galaxy M_{25} is better than that between M_{BH} and baryonic mass.

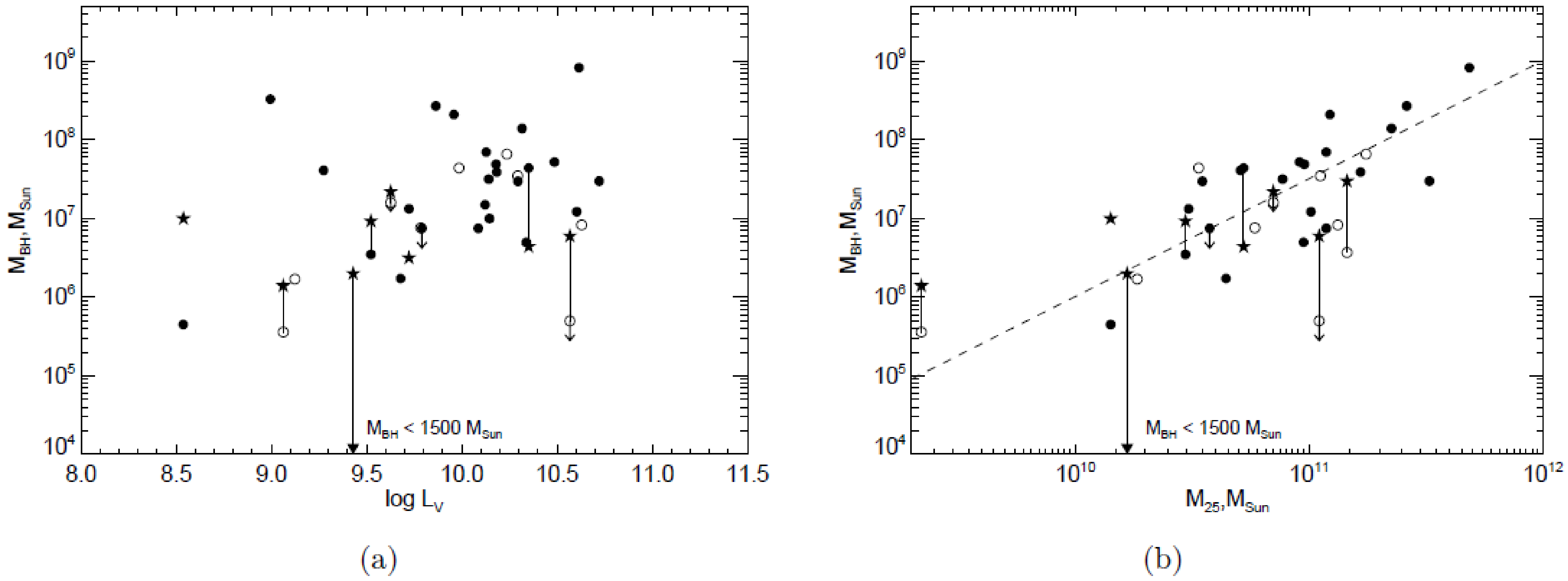


Figure 4: A comparison of the SMBH masses with (a) the total luminosities of parent galaxies L_V and (b) the dynamical (indicative) masses within the optical radius $M_{25} = V_{far}^2 R_{25}/G$. The notation is the same as in Fig. 2.

Masses of BHs and Nuclear Clusters are only weakly correlated with asymptotic rotational velocity V_{FAR}, but they are in good correlation with the rotational velocity at R ≈ 1 kpc (characteristic dimension of dynamically separated nuclear disk). It should be noted, that mean density of matter in the region with R ≈ 1 kpc is determined by V(R = 1 kpc).

Masses of BHs and Nuclear Clusters are in good correlation with integral (indicative) masses of the galaxies in the limit of their optical radii R_{25} (this mass includes baryonic and dark matter).

All correlations between the mass of central supermassive object and parameters of the host galaxy became more regular for summary mass of central object (supermassive BH + Nuclear Cluster).

Dependence of M_{BH} on V(R = 1 kpc) allows us to suggest that supervassive BH together with buldge is formed as a result of "monolithic" collapse of central gaseous part of the forming galaxy (Zasov, Cherepashchuk, Katkov, 2011).

See, for example, results of computer simulations:

Xu et al., 2007

Cook et al., 2009

VI. Conclusion.

A big progress in observations of stellar mass BHs and supermassive BHs has been achieved during last 40 years. Hundreds of reliable BH candidates have been discovered up to now.

All observational appearances of BH candidates are in excellent agreement with Einstein General Relativity.

Taking into account observational selection effects we can estimate the full number of stellar mass BHs in our Galaxy as $\sim 10^7$. For the mean mass $M_{BH} \approx 9 - 10\ M_{Sun}$ it is $\sim 10^8\ M_{Sun}$ or 0.1% of the baryonic mass in our Galaxy.

VII. Future investigations (stellar mass BHs).

- Development of the theory of disk accretion (e.g. Narayan et al., 1997; Bisnovatyi-Kogan and Lovelace, 1997; Blanford and Begelman, 1999).
- Optical observations of X-ray binaries in other galaxies using new generation 8 – 10 meters telescopes (e.g. Orosz et al., 2007).
- X-ray investigations of low-frequency and high-frequency QPOs in X-ray binaries (e.g. Titarchuk and Osherovich, 2000). HFQPO are related to the physical processes in strong gravity near the BH event horizon (e.g. McClintock and Remillard, 2003).
- Determination of spins of BHs (Narayan and McClintock, 2012).

VII. Future investigations (supermassive BHs).

- Search for binary supermassive BHs in galactic nuclei (e.g. Sanders and Mirabel, 1996; Komossa et al., 2003).
- Observations of X-ray and ultraviolet-optical flares from the tidal disruption of stars near supermassive BHs in galactic nuclei (Komossa et al., 1997, 2002; Gezari et al., 2012).
- Investigations of BH shadow image and extreme gravitational lensing effects near supermassive BHs in galactic nuclei (e.g. Doelman et al., 2008; Zakharov et al., 2005; Backwith and Done, 2005):

  VLBI and Space interferometers MILLIMETRON, MAXIM.